

Evidence for a Physically Compact Narrow-Line Region in the Seyfert 1 Galaxy NGC 5548¹

Steven B. Kraemer^{2,3}, D. Michael Crenshaw^{2,4}, Alexei V. Filippenko⁵,
and Bradley M. Peterson⁶

Received _____; accepted _____

¹Based on observations with the NASA/ESA *Hubble Space Telescope*, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

²Catholic University of America, NASA/Goddard Space Flight Center, Code 681, Greenbelt, MD 20771.

³Email: stiskraemer@yancey.gsfc.nasa.gov.

⁴Email: crenshaw@buckeye.gsfc.nasa.gov.

⁵Department of Astronomy, University of California, Berkeley, CA 94720-3411, alex@astro.berkeley.edu.

⁶Department of Astronomy, The Ohio State University, Columbus, OH 43210, peterson@astronomy.ohio-state.edu.

ABSTRACT

We have combined *HST*/FOS and ground-based spectra of the Seyfert 1 galaxy NGC 5548 to study the narrow emission lines over the 1200 – 10,000 Å region. All of the spectra were obtained when the broad emission line and continuum fluxes were at an historic low level, allowing us to accurately determine the contribution of the narrow-line region (NLR) to the emission lines. We have generated multicomponent photoionization models to investigate the relative strength of the high ionization lines compared to those in Seyfert 2 galaxies, and the weakness of the narrow Mg II λ 2800 line.

We present evidence for a high ionization component of NLR gas that is very close to the nucleus (~ 1 pc). This component must be *optically thin* to ionizing radiation at the Lyman edge (i.e., $\tau_0 \approx 2.5$) to avoid producing [O I] and Mg II in a partially ionized zone. The very high ionization lines (N V, [Ne V], [Fe VII], [Fe X]) are stronger than the predictions of our standard model, and we show that this may be due to supersolar abundances and/or a “blue bump” in the extreme ultraviolet (although recent observations do not support the latter). An outer component of NLR gas (at only ~ 70 pc from the continuum source) is needed to produce the low ionization lines. We show that the outer component may contain dust, which further reduces the Mg II flux by depletion and by absorption of the resonance photons after multiple scatterings.

We show that the majority of the emission in the NLR of NGC 5548 must arise within about ~ 70 pc from the nucleus. Thus, the NLR in this Seyfert 1 galaxy is very physically compact, compared to the typical NLR in Seyfert 2 galaxies.

Subject headings: galaxies: individual (NGC 5548) – galaxies: Seyfert

1. Introduction

NGC 5548 is a bright, low-redshift ($z = 0.0172$) Seyfert 1 galaxy that has received a considerable amount of attention over the past decade. In particular, NGC 5548 has been the subject of a number of intensive spectroscopic monitoring campaigns in the optical and UV (Korista et al. 1995). These efforts have yielded important results on the nature of the continuum source and the size, geometry, and kinematics of the broad-line region (BLR), for which the responsivity peaks at about 20 light days from the nucleus (Peterson et al. 1994). Little attention has been paid to the narrow-line region (NLR) in NGC 5548, however, although it could lead to a better understanding of the circumnuclear environment at much greater distances from the nucleus of this otherwise well-studied active galaxy.

In general, studies of the NLR in active galaxies are important for understanding the nature of the NLR clouds and the interaction of the central continuum source with the surrounding galaxy on large scales. Emission-line studies and detailed photoionization modeling are particularly useful for determining the range of physical conditions and reddening amongst the NLRs in active galaxies. A comparison of the NLR properties in Seyfert 1 and Seyfert 2 galaxies should be helpful in testing unified theories, which postulate that the two types are the same object viewed from different perspectives, such that the continuum source and BLR are “hidden” in Seyfert 2 galaxies (Miller & Goodrich 1990; Antonucci 1993). If this basic hypothesis is correct, then the intrinsic properties of the NLRs in Seyfert 1 and Seyfert 2 galaxies should *not* show large systematic differences.

The narrow lines in Seyfert 1 galaxies are more difficult to measure than in Seyfert 2 galaxies, due to blending with the broad lines. However, given spectra with sufficient signal-to-noise ratio and spectral resolution, these components can be isolated and measured reasonably well (Crenshaw & Peterson 1986). Measurements of the narrow lines in the optical are given by Cohen (1983) for a large number of Seyfert 1 galaxies. In the UV, these

measurements were difficult with the low spectral resolution of the *International Ultraviolet Explorer (IUE)*, but are possible with instruments on the *Hubble Space Telescope (HST)*, such as the Faint Object Spectrograph (FOS).

The FOS UV spectra of NGC 5548 presented in a previous paper (Crenshaw, Bogges, & Wu 1993; hereafter Paper I) provide a good starting point for detailed studies of the NLR in a Seyfert 1 galaxy. These observations happened to occur at a time when the broad emission lines (and continuum fluxes) were at an historic low in the UV, and the contrast between the broad and narrow components is thereby enhanced. Paper I gives the UV spectrum and measurements of the broad and narrow lines in NGC 5548. Relative to the other narrow lines, C IV $\lambda 1549$ is much stronger in NGC 5548 than in Seyfert 2 galaxies, indicating a higher ionization parameter and/or harder continuum in the NLR of NGC 5548. Narrow Mg II $\lambda 2800$ emission is very weak or absent in NGC 5548, and Paper I presents two possible explanations: 1) the NLR clouds lack the presence of a partially-ionized zone (i.e., they are optically thin to ionizing radiation), and/or 2) dust grains are present in the NLR clouds, and the Mg II flux is weak due to depletion and/or destruction from multiple scatterings and eventual absorption of the photons by dust (Kraemer & Harrington 1986; Ferland 1992).

We now have the opportunity to investigate the preliminary results from Paper I in more detail, by including ground-based optical spectra and photoionization models. From the ground-based monitoring campaigns, we have selected spectra that cover the full optical range (3000 – 10,000 Å) and were observed around the same time period as the UV data, when the broad-line fluxes were very low. The combination of optical and UV lines provides a wide range of emission-line diagnostics, as well as an opportunity to deredden the lines using the He II recombination lines. We can then use multicomponent photoionization models to match the dereddened line ratios and probe the physical conditions in the NLR

of NGC 5548.

2. Observations and Data Analysis

2.1. UV and Optical Spectra

We obtained the FOS UV spectra of NGC 5548 through a $1''.0$ circular aperture on 1992 July 5 UT. Paper I gives the details of the observations and measurements, along with the UV spectrum and emission-line fluxes (with associated errors). The observations were made prior to the installation of COSTAR on *HST*, so near-simultaneous *IUE* spectra were used to adjust the absolute flux levels of the FOS spectra. As noted in Paper I, the scale factors needed to bring the FOS continuum fluxes up to the *IUE* levels are around $1.4 - 1.5$, which are somewhat higher than the values of $1.1 - 1.3$ for our other Seyfert observations. We concluded that the Seyfert nucleus may not have been accurately centered in the aperture. Koratkar et al. (1996) suggest that another possible explanation for the discrepancy in absolute fluxes is nonlinearity in the *IUE* detectors. However, we have seen no evidence for this possibility in other observations at these flux levels, so we have no reason to distrust the *IUE* fluxes. In addition, reprocessed versions of these spectra that we obtained from the *HST* and *IUE* archives have not changed the original fluxes by more than 10%, so we continue to use the values from Paper I. Some of the emission lines in Paper I have only a single number quoted for the flux (as opposed to separate values for the broad and narrow components); a single value represents the narrow-line contribution, since the broad component is either not present or too weak to be detected in these cases.

We selected two optical spectra obtained during a four-year monitoring campaign on NGC 5548 (Peterson et al. 1994), from a time interval of ~ 30 days when the $H\beta$ and continuum light curves were at their lowest levels to date. The spectra were chosen on the

basis of their large wavelength coverage (3000 - 10000 Å), high signal-to-noise ratio (≥ 50 per resolution element in the continuum at 5200 Å), and acceptable resolution (~ 8 Å). The spectra were obtained through a $4''.0 \times 10''.0$ aperture with the 3.0-m Shane telescope + Kast spectrograph on 1992 April 21 and 1992 May 23 UT. Additional details on the observations are given by Peterson et al. (1994). The absolute flux levels were adjusted by scaling the optical spectra so that the [O III] $\lambda 5007$ flux is 5.58×10^{-13} ergs s $^{-1}$ cm $^{-2}$, a value determined from observations through large apertures on spectrophotometric nights (Peterson et al. 1991). The scale factors we used are 1.36 for the 1992 April 24 spectrum and 1.01 for the 1992 May 23 spectrum.

Plots of the optical spectra are shown in Figure 1 (the UV spectrum is shown in Paper I). The contrast between the broad and narrow components of the permitted emission lines is most clearly seen in H β . The 1992 April 21 spectrum was obtained at an historic low level, with a continuum flux of $F_{\lambda}(5100 \text{ Å}) = 5.5 \times 10^{-15}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$ and total H β flux of $F(\text{H}\beta) = 3.2 \times 10^{-13}$ ergs s $^{-1}$ cm $^{-2}$. The flux levels are a little higher for the 1992 May 23 spectrum with $F_{\lambda}(5100 \text{ Å}) = 6.0 \times 10^{-15}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$ and $F(\text{H}\beta) = 3.7 \times 10^{-13}$ ergs s $^{-1}$ cm $^{-2}$. At the time of the FOS observations on 1992 July 5, the continuum and H β fluxes were close to the same levels as those from the second optical spectrum, according to the light curves of Peterson et al. (1994).

Although the optical aperture is much larger than the one used for the UV observations, we have substantial evidence that it does not contain much additional NLR flux. Unfortunately, there are no *HST* narrow-band images in [O III] or other strong lines that could be used to directly determine the distribution of narrow-line emission close to the nucleus. However, there is significant evidence that the apparent size of the NLR is very small in NGC 5548. Peterson et al. (1995) find from a ground-based image that the [O III] emission is pointlike, given a point-spread function that is characterized by a width

of $2''.0$ (FWHM). In addition, Wilson & Ulvestad (1982) show that in an aperture that is $4''.2$ in diameter, the [O III] $\lambda 5007$ fluxes at positions offset from the nucleus by $4''.5 - 6''$ are about 100 times weaker than the nuclear flux. More importantly, in Paper I we found that the strongest UV lines in the *IUE* $20'' \times 10''$ aperture have fluxes that are only $\sim 20\%$ higher than those in the FOS $1''.0$ aperture. Thus, the observed UV to optical line ratios that we quote are at most 20% too low, which has little effect on our comparisons with the model results.

In order to measure the flux of each narrow optical line, we used a local baseline determined by linear interpolation between adjacent continuum regions or broad profile wings (in the case of profiles consisting of broad and narrow components). For severely blended lines like $H\alpha$ and [N II] $\lambda\lambda 6548, 6584$, we used the [O III] $\lambda 5007$ profile as a template to deblend the lines (see Crenshaw & Peterson 1986). The adopted flux for each narrow component is the average of the values from each of the two spectra.

We determined the reddening of the narrow emission lines from the He II $\lambda 1640/\lambda 4686$ ratio and the Galactic reddening curve of Savage & Mathis (1979). For the temperatures and densities typical of the NLR, the He II lines are due to recombination, and this particular ratio only varies from 6.3 to 7.6 (Seaton 1978); we adopt an intrinsic value of 7.2, consistent with our model values (Section 3). The observed He II $\lambda 1640/\lambda 4686$ ratio is 5.5 ± 1.6 , which yields a reddening of $E_{B-V} = 0.07 \text{ mag }^{+0.09}_{-0.06}$. The portion of the reddening that is due to our own Galaxy is $E_{B-V} = 0.03 \text{ mag}$, determined from a neutral hydrogen column density of $N_{HI} = 1.6 \times 10^{20} \text{ cm}^{-2}$ (Murphy et al. 1996) and the relationship $E_{B-V} = N_{HI}/5.2 \times 10^{21} \text{ cm}^{-2}$ (Shull & Van Steenburg 1985). We note that the intrinsic reddening of the narrow emission lines in this Seyfert 1 galaxy, $E_{B-V} \approx 0.04 \text{ mag}$, is much smaller than typical values of $0.2 - 0.4 \text{ mag}$ obtained for Seyfert 2 galaxies (MacAlpine 1988; Ferland & Osterbrock 1986; Kraemer et al. 1994).

We determined errors in the dereddened ratios from the sum in quadrature of the errors from three sources: photon noise, different reasonable continuum placements, and reddening. Errors in the optical ratios are dominated by continuum placement, whereas errors in the UV to optical ratios are due to both continuum placement and uncertainties in the reddening correction. Errors in the weak lines in both regions also have a significant contribution from photon noise. As we discussed earlier in this section, there are some possible sources of systematic error in the UV to optical line ratios, on which we placed upper limits of $\sim 20\%$.

Table 1 gives the observed and dereddened narrow-line ratios relative to $H\beta$, and errors in the dereddened ratios. Cohen (1983) gives the next most comprehensive list of optical line ratios; in general, Cohen’s observed ratios agree with ours to within the errors. A number of investigators have independently determined the narrow $H\beta/[O\ III]\ \lambda 5007$ ratio in NGC 5548 (Cohen 1983; Crenshaw & Peterson 1986; Peterson 1987; Wamsteker et al. 1990; Rosenblatt et al. 1992; Wanders & Peterson 1996): these values range from 0.10 to 0.15, compared to our value of 0.12 ± 0.01 .

2.2. The Ionizing Continuum

Estimates of the ionizing continuum are needed as input values for the photoionization models of the NLR. We choose the continuum data points given by Krolik et al. (1991), since they represent the historic mean levels for this object. As always, the greatest uncertainty is the shape of the extreme ultraviolet (EUV) continuum. Figure 2 gives the UV continuum point closest to the EUV region, at $1340\ \text{\AA}$, and the X-ray continuum points from Krolik et al. (cf. Turner & Pounds 1989; Clavel et al. 1991) in terms of luminosity ($\text{ergs s}^{-1}\ \text{Hz}^{-1}$), which we have adjusted for a Hubble constant of $H_0 = 75\ \text{km s}^{-1}\ \text{Mpc}^{-1}$. The dotted line in Figure 1 gives Krolik et al.’s continuum fit in the EUV, which is a power

law determined from the UV data along with an exponential cutoff designed to meet the first X-ray point. We prefer a fit with two power laws (in the form $L_\nu = K\nu^\alpha$), given the evidence for an upturn in the spectrum at energies smaller than 1 – 2 keV (i.e., a soft X-ray excess). A fit to these data yields $\alpha = -1.40 \pm 0.03$ in the EUV and soft X-rays, and $\alpha = -0.40 \pm 0.03$ in the hard X-rays; the break point is at $\nu = 10^{17.1} \text{ Hz}^{-1}$ (1.3 keV).

NGC 5548 was monitored by the *Extreme Ultraviolet Explorer* (*EUVE*) over a two month period during 1993 March – May (Marshall et al. 1997). During this time, the EUV flux varied by a factor of four from peak to minimum, and the average flux (corrected for Galactic neutral hydrogen absorption) was $135 \mu\text{Jy}$ at $\sim 76 \text{ \AA}$. These observations provide an important constraint on the EUV ionizing continuum, but were not used directly in our continuum fit for two reasons. First, the neutral hydrogen absorption due to our Galaxy is well known (see the previous section), but there could be additional absorption along the line of sight. Second, the *EUVE* flux, averaged over two months, may not be representative of the average flux over many years. Given these caveats, we plot the *EUVE* continuum point in Figure 2 for comparison with our adopted continuum; the error bar was determined from an estimate of $\pm 10\%$ uncertainty in Galactic N_{HI} (see Murphy et al. 1996). The *EUVE* point is slightly higher than the continuum fits in Figure 2, but appears to be consistent with our and Krolik et al.’s adoption of a relatively steep continuum. If we use Krolik et al.’s continuum or a continuum formed by joining the UV, *EUVE*, and X-ray points with line segments (in log space), the total EUV flux increases by factors of only 1.19 and 1.30, respectively, and the flux at the frequency of the *EUVE* observation increases by factors of 1.40 and 1.84, respectively. The effects of adopting these other continua are small, and will be discussed later in the paper.

3. Photoionization Models

In modeling the narrow-line emission of NGC 5548, we have adhered to our basic philosophy of keeping the number of free parameters to a minimum, by using the available observational constraints and the simplest assumptions possible. The parameters are varied until the best agreement is obtained with the observed line ratios, and additional input parameters are only included if they are needed to provide a reasonable match to the majority of the lines. Discrepancies between the model predictions and specific lines are then investigated to provide further insight into the physical conditions. In some cases we generate variations on the standard model using additional parameters (such as dust) or nonstandard values of the initial parameters (such as nonsolar abundances) to illustrate our ideas for resolving the discrepancies.

3.1. Methodology

The basic modeling methodology that we employ is described in Kraemer et al. (1994) and the details of the photoionization code are given in Kraemer (1985). To review the major points, we assume plane parallel geometry, which is reasonable if the gas is ionized by radiation from a central source at a distance that is large compared to the extent of the cloud. The gas is assumed to be atomic (i.e., there is no molecular component). For radiation bounded models, we stop the integration into the slab when the electron temperature falls below 5000 K and there is no longer any significant line emission. The emission line photon escape is through the ionized face of the slab. Details of the treatment of dust in the models are described in Kraemer (1985). Since the work of Kraemer et al. (1994), we have added iron to the elements modeled in the code. The atomic data that we used can be found in Pradhan & Peng (1994), and references contained therein, as well as through Ferland’s “Cloudy and Associates” World Wide Web site

(<http://www.pa.uky.edu/~gary/cloudy>). The final output of these models is an emission line spectrum. The line strengths are tabulated relative to $H\beta$. In addition, the model gives the volume emissivity of $H\beta$, from which we can determine the mass of gas required to produce the observed line emission, the efficiency of production of $H\beta$ photons, and an estimate of the covering factor.

In order to keep the input parameters to a minimum, we kept two of them fixed for our standard model: the shape of the ionizing continuum and the abundances. We used the simplest possible ionizing continuum consistent with the observations, as described in Section 2.2. In addition, we have assumed solar elemental abundances for the standard model as follows (see Lambert & Luck 1978): He = 0.1, C = 3.4×10^{-4} , O = 6.8×10^{-4} , N = 1.2×10^{-4} , Ne = 1.1×10^{-4} , S = 1.5×10^{-4} , Si = 3.1×10^{-5} , Mg = 3.3×10^{-5} , Fe = 4×10^{-5} (relative to hydrogen by number).

Our photoionization models are parameterized in terms of the density of atomic hydrogen (N_H) and the dimensionless ionization parameter at the illuminated face of the cloud:

$$U = \int_{\nu_0}^{\infty} \frac{L_{\nu}}{h\nu} d\nu / (4\pi D^2 N_H c), \quad (1)$$

where L_{ν} is the frequency-dependent luminosity of the ionizing continuum, D is the distance between the cloud and the ionizing source, and $h\nu_0 = 13.6$ eV.

We show that we must add two enhancements to our standard model to obtain an acceptable match to the observations. First, we need two components of gas, characterized by different ionization parameters and densities. Second, we show that the inner component must be optically thin (i.e., radiation bounded) at the Lyman edge (13.6 eV). We are then able to vary the ionization parameter and density of each component to match the

observations. Of course, the resulting standard model is an oversimplification, since it is likely that the NLR clouds are characterized by a number of different ionization parameters, densities, and optical depths. We have effectively averaged the initial conditions for each of these components to fit the largest selection of line ratios. Given this simplification, the two-component model gives a surprisingly good fit to the observations.

The narrow-line spectrum of NGC 5548 is dominated by high ionization lines, such as C IV $\lambda 1549$, N V $\lambda 1240$, and [Ne V] $\lambda\lambda$ 3346, 3426, as well as the coronal lines of [Fe VII] and [Fe X]. This indicates that there is a high ionization component relatively near the central source, but presumably outside the BLR, since these lines are much narrower ($\leq 500 \text{ km s}^{-1}$ FWHM) than the broad lines ($\sim 5000 \text{ km s}^{-1}$ FWHM). Also present in the spectrum are relatively strong lines of [N II] $\lambda\lambda$ 6584, 6548 and [O II] $\lambda 3727$. These are typical of the narrow emission line regions of many Seyfert 2 galaxies (Koski 1978; Shuder & Osterbrock 1981), and presumably arise in a component of relatively low ionization and low density.

The choice of density for these models is based on the relative strengths of certain forbidden emission lines in the spectrum of NGC 5548. An emission line will not be an important coolant in gas with sufficiently large electron density that collisional de-excitation of the line will dominate over radiative transition (see Osterbrock 1989). For example, the observed [Ne V] $\lambda 3426/\text{H}\beta$ ratio indicates that the density of the component in which that emission originates must be less than $\sim 5 \times 10^7 \text{ cm}^{-3}$ (DeRobertis & Osterbrock 1984). Given the hardness of the ionizing continuum, one would expect high temperatures in this highly ionized gas. The lower limit on the density of this component can be estimated from the relative strength of the [O III] $\lambda 5007$ emission. The ratio of [O III] $\lambda 5007$ / [Ne V] $\lambda 3426$ is less than 5, which indicates either low density, highly ionized gas, as is often seen in the extended NLR of Seyfert 2 galaxies (Storchi-Bergmann et al. 1996), or density greater than

10^6 cm^{-3} and some collisional suppression of the $\lambda 5007$ line. The ratio of [O III] $\lambda 4363/\lambda 5007$ is very high (~ 0.09). In the low density limit, this ratio is $\sim 7 \times 10^{-3}$ at a temperature of 10^4 K (Osterbrock 1989). At this low density, it is unlikely that temperatures consistent with photoionization equilibrium can increase this ratio to the observed value, and probable that the large $\lambda 4363/\lambda 5007$ ratio is due to the fact that some of this emission arises in gas of high density (i.e., $> 10^6 \text{ cm}^{-3}$). At this density and level of ionization, the [N II] $\lambda \lambda 6548, 6584$ emission from this component will be negligible, so there must be a lower ionization and lower density component present. In order for the [N II] lines to be among the principal coolants from this component, its density must be less than $1 \times 10^5 \text{ cm}^{-3}$. Other studies (cf. Filippenko & Halpern 1984; Filippenko 1985; Kraemer et al. 1994) have shown that a range of densities in the NLR of Seyfert galaxies is likely, so it is not surprising that this condition exists in NGC 5548.

To summarize, the range in density, along with the presence of emission lines from a wide range of ionization states, indicates that more than one model component is needed to fit the NLR spectrum of NGC 5548. The existence of strong high ionization lines such as C IV $\lambda 1549$, N V $\lambda 1240$, and [Ne V] $\lambda \lambda 3346, 3426$, and our evidence for high densities in the region that they are produced, requires a component of gas relatively close to the central source. The weakness of Mg II $\lambda 2800$ and [O I] $\lambda \lambda 6300, 6364$ indicate that these gas clouds lack a significant partially ionized zone, and therefore must be *optically thin* to the ionizing radiation (or “matter bounded”). We further investigate the conditions in these two components below.

3.2. Model Results and Comparison to Observations

Our approach in modeling NGC 5548 was to fit the high ionization component first and then add components as needed to fit the lower ionization lines (in the end, only one

additional component was needed). Given the constraints and assumptions described in the previous section, we arrived at values of $N_H = 1 \times 10^7 \text{ cm}^{-3}$ and $U = 10^{-1.5}$ for the high ionization component. Substantially lower densities would result in [O III] $\lambda 5007$ being too strong, and higher densities would quench the [Ne V] emission. A higher ionization parameter is possible but, given our EUV continuum, would not increase the relative strengths of any of the high ionization lines other than [Fe X] $\lambda 6374$, at the expense of putting this component at distances much closer than $\sim 1 \text{ pc}$ from the continuum source (see Section 4). Models were run to varying optical depth at the Lyman limit τ_0 , with the constraint that the Mg II and [O I] lines could not become too strong. After comparing the results of models run with $\tau_0 = 1.5$ to 10, we found that $\tau_0 = 2.5$ gave the best fit. The emission line spectrum from this model, INNER, is given in Table 2.

A second component, OUTER, was needed to fit the lower ionization lines. We found that $U = 10^{-2.5}$ and $N_H = 2 \times 10^4 \text{ cm}^{-3}$ gave a good simultaneous fit to the [O III] $\lambda 5007$ /[O II] $\lambda 3727$ and [N II] $\lambda 6584$ /H β ratios. Unlike our models for Mrk 3 and I Zw 92 (Kraemer & Harrington 1986; Kraemer et al. 1994), there was no need to add a third component for NGC 5548, since there is no obvious contribution from a component of very low density ($< 10^3 \text{ cm}^{-3}$) low ionization gas, such as very strong [O II] $\lambda 3727$ and [N I] $\lambda 5200$ lines. The resulting emission line spectrum from OUTER is also included in Table 2. (We will discuss two variations on INNER and OUTER in the next section.)

In order to fit the observed (and dereddened) narrow-line spectrum of NGC 5548, we combined the output spectrum of the two standard components INNER and OUTER. In previous studies, we attempted to weigh the contributions from each component to fit specific emission line ratios. For the model of NGC 5548, we simply took an equal contribution from INNER and OUTER. The relative simplicity of the narrow-line spectrum and lack of a strong contribution from very low-ionization gas makes such a simple fit

possible. The combined spectrum is given, along with the dereddened observed spectrum for comparison, in Table 3 (horizontal lines in the table indicate that the models do not predict the strengths of these emission lines).

Comparison of the model predictions to the dereddened observed spectrum in Table 3 shows agreement, to within the errors, for most of the lines. In particular, these include C IV $\lambda 1549$, He II $\lambda 1640$, [O II] $\lambda 3727$, [Ne III] $\lambda 3869$, [N II] $\lambda 6584$, and the Balmer decrement. In radiation bounded gas, the ratio of the He II lines to $H\beta$ is strongly dependent on the shape of the ionizing continuum, because neutral hydrogen is the dominant absorber of ionizing radiation between 13.6 eV and 54.4 eV, while above 54.4 eV, singly ionized helium dominates. If there is a component of matter bounded gas, He II/ $H\beta$ is less easily predicted. The accuracy of our fit to this ratio indicates that the relative contributions of the matter and radiation bounded components are approximately correct, given the observational constraints on the ionizing continuum. The fact that we have a reasonable fit for lines that span a wide range of ionization and critical densities supports our values for density and ionization parameter. Most of the discrepancies between the observations and models are in the lowest and highest ionization lines, which we will address below.

3.3. Discrepancies and Possible Explanations

First, we address differences between the predicted and observed ratios for the low ionization lines. The Mg II $\lambda 2800$ and [O I] $\lambda\lambda 6300, 6364$ lines are still predicted to be too strong by our standard model, by factors ≥ 6 and 2.5, respectively. Nearly all this emission is coming from OUTER. Two factors determine the strength of the [O I] lines: the hardness of the ionizing continuum and the physical depth of the emission line clouds. Since it appears that we have a good fit for the ionizing continuum, the weakness in the observed [O I] lines gives a limit on the depth of the clouds. Truncating the integration

of OUTER at $\tau_0 \approx 1000$ would give a better fit to the [O I] without affecting the other important line ratios. This results in a cloud depth of $\sim 2.5 \times 10^{15}$ cm. The overprediction of the Mg II $\lambda 2800$ line strength presents a somewhat different problem. In order to reduce the contribution of this line from INNER, we assumed a matter bounded model for this component. To provide a better match to the observation of little or no Mg II emission, we can reduce the model contribution by modifying OUTER. The Mg^+ emissivity is greatest near the H^+/H^0 transition zone in OUTER, so a simple truncation at much lower optical depths is not feasible, as it would have a much greater effect on the other line ratios.

An obvious explanation for the weak observed Mg II is depletion of the magnesium into dust grains, along with suppression of the resonance photons by multiple scatterings and eventual absorption by dust. This was suggested in Paper I (cf. Kraemer & Harrington 1986; Ferland 1992). For comparison with our standard model, we generated a version of OUTER that includes dust, assuming a dust to gas ratio that is 30% of that found in the Galactic interstellar medium, with equal amounts of graphite and silicate grains and accompanying depletions. These assumptions were made to avoid biasing our results by simply having all of the Mg depleted into dust grains. We assumed relative element depletions as calculated by Seab & Shull (1983), and the grain size distributions determined by Mathis et al. (1977) and Draine & Lee (1984); details of the treatment of dust in the code are given by Kraemer (1985). The results of the model are given in Table 2, and not only show a significant drop in the relative strength of Mg II $\lambda 2800$, but also a drop in the $\text{Ly}\alpha$ strength, as is expected due to the preferential dust absorption of multiply scattered UV resonance lines. The lower $\text{Ly}\alpha/\text{H}\beta$ ratio is a better fit to the observations. A substantially larger dust-to-gas ratio than we assumed would result in a $\text{Ly}\alpha/\text{H}\beta$ ratio that is lower than observed. Therefore, it is likely that there is some dust mixed in with the low-ionization gas, although with a lower dust to gas ratio than found in the ISM, and that depletion coupled with the resonance line suppression explain the weak Mg II.

Second, we address discrepancies in the high ionization lines. Specifically, the lines of N V, [Ne V], [Fe VII], and [Fe X] are too weak by factors of 2 to 4 compared to the observations. As we mentioned earlier, the density is well constrained, so increasing the ionization parameter brings the gas well within 1 pc, into the realm of the BLR. However, these lines are relatively narrow ($\text{FWHM} \leq 500 \text{ km s}^{-1}$, see Moore et al. 1996) and they are not likely to arise very close to the BLR. The strengths of the high ionization lines can also be enhanced relative to $\text{H}\beta$ by truncating the integration of INNER at a lower optical depth. However, this has the problem of enhancing the He II emission relative to $\text{H}\beta$ in the model. More likely solutions to the problem of underpredicting the high ionization lines include 1) shock ionization, 2) a large “blue bump” in the EUV continuum, or 3) supersolar abundances.

Predicting the strengths of the coronal lines has always been a problem with simple photoionization models, as Viegas-Aldrovandi & Contini (1989) discuss in some detail for the Fe lines. They suggest that there may be shocked gas mixed in with the photoionized clouds and that these high ionization lines may arise there. Although this is certainly a possible factor, there may be other plausible explanations which avoid adding another level of complexity.

An obvious way in which the coronal lines might be enhanced is if there were a component of ionizing radiation that contributed significantly at energies between 100 and 500 eV. Although there has been some speculation about the presence of a “blue bump” in the EUV, recent work by Zheng et al. (1997) on low-redshift quasars shows that the *near* EUV continuum is likely to be much steeper than previously supposed. In NGC 5548, the *EUVE* continuum point in Figure 2 is further confirmation that a large blue bump is not present in the spectrum of NGC 5548. Another possibility may be diffuse radiation from the intercloud medium. Tran (1995) has shown that there may be a contribution to the

continuum radiation in some Seyfert 2 galaxies from thermal emission from the intercloud medium responsible for the scattering of the hidden BLR emission into the observer’s line of sight. If a similar medium with temperatures $\approx 5 \times 10^5$ K exists in the NLR of NGC 5548, it is possible that free-free radiation and line emission that arise within it may contribute to the ionization of the inner narrow-line gas. Although this component would be weak compared to the continuum radiation emitted by the central source, it could have a significant local contribution to the ionization balance of clouds existing within this inner region. However, recent observations suggest that the extended UV continuum seen in some Seyferts may be due to starbursts (Heckman et al. 1997), which would not contribute to the high ionization lines.

In studies of medium redshift QSOs, Ferland et al. (1996) found evidence of supersolar abundances. There is no direct evidence of elemental enhancements in Seyfert galaxies, but it is certainly not implausible, particularly near the nucleus, where the most intense activity occurs. As Oliva (1996) points out, the coronal line emission will be enhanced proportionally to the abundance of the atomic species. As a comparison, we ran a version of INNER with a heavy element abundance that is twice solar, and the results are shown in Table 3. In particular, the relative strengths of the [Fe VII] and [Ne V] lines have increased, while many lines, such as C IV $\lambda 1549$ and C III] $\lambda 1909$, show little change. It is possible, then, that the observed strength of some of these lines is in part due to enhanced abundances. Note that we have not attempted to adjust the increase in abundances to fit assumptions about the type of star formation that might be expected.

4. Discussion

From our standard model, we can estimate several global properties of the NLR in NGC 5548, including the covering factor and physical size, in addition to more local

properties, including optical depth and presence of dust. We determine the covering factor of the NLR gas from the observed and model values of the “conversion efficiency”, η , which is the ratio of $H\beta$ photons to ionizing photons. The covering factor is given by $C = \eta(\text{observed})/\eta(\text{model})$. A value of $C > 1$ would indicate that the ionizing radiation is anisotropic, which we would not expect to be the case for a Seyfert 1 galaxy, since the central source is seen directly in such objects. Assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the observed $H\beta$ flux corresponds to a luminosity of $3.8 \times 10^{40} \text{ ergs s}^{-1}$, or $9.3 \times 10^{51} H\beta$ photons s^{-1} . From the continuum observations described in section 2.2, we calculate a total luminosity of ionizing photons of $1.09 \times 10^{54} \text{ s}^{-1}$. This yields an observed $\eta = 0.009$. Our fit to the observed emission line spectrum assumed that each component in our model contributed 50% of the $H\beta$ emission. The resulting values of η were 0.06 for INNER and 0.11 for OUTER, and the covering factors are 0.07 and 0.04, respectively, so $C(\text{NLR}) = 0.11$. The value is small compared to those found for Seyfert 2 galaxies, which are often > 1 (Kinney et al. 1991; Kraemer et al. 1994), and there is no evidence for anisotropic radiation. Note that this estimate of covering factor does not include the BLR clouds, which contribute at least 50% of the flux in many of the strong lines, even when NGC 5548 is in its lowest state (Paper I).

Given the ionization parameters and densities of the two components from our standard model, as well as the ionizing luminosity, the characteristic sizes (i.e., radii) for the two emitting regions are 1 pc for INNER, and 70 pc for OUTER. (Using the higher continuum luminosity given by the *EUVE* point in Figure 2 would increase these values by a factor of only $\sqrt{1.30}$, or 1.14.) Thus, the NLR of NGC 5548 is *physically* compact, since the size of OUTER is much smaller than typical values of 200 – 1000 pc determined for Seyfert 2 galaxies, using the same methods that we have described in this paper (Kraemer & Harrington 1986; Kraemer et al. 1994). Although there have been reports of extended emission from NGC 5548 (Wilson et al. 1989), the contribution to the integrated emission

line spectrum from this region is small (Peterson et al. 1995); we estimated the contribution to the narrow UV lines outside of a $1''$ aperture (330 pc for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) to be only $\sim 20\%$. This is consistent with our finding that the majority of the narrow emission must arise in a region with a “diameter” of 140 pc.

Pogge (1989) and Schmitt & Kinney (1996) claim that the *apparent* size of the NLR in a Seyfert 1 galaxy is typically much smaller than that of a Seyfert 2 galaxy, although this may be due to a selection effect, since most of the Seyfert 2s in the HST archive were selected on the basis of their extended emission (Wilson 1997). Nevertheless, it is clear that the majority of the Seyfert 1 galaxies in these studies are apparently compact. This cannot be explained by viewing angle alone, since the opening angles of the presumed ionization cones are large, and in the simplest version of the unified model, the apparent extent of most Seyfert galaxies should be much larger, even if viewed “pole-on” (Schmitt & Kinney 1996). Our results show that a possible explanation for the small apparent size of the NLRs in many Seyfert 1 galaxies is that they are truly (i.e., physically) compact. Schmitt & Kinney explain this phenomenon as a result of the orientation of the obscuring torus with respect to the plane of the galaxy. However, their model does not explain the dominance of the high ionization lines in NGC 5548 and many other Seyfert 1 galaxies, a feature not generally seen in Seyfert 2 galaxies (Koski 1978; Shuder & Osterbrock 1981). Thus, if the unified model applies we might expect that the narrow emission line spectrum of this Seyfert 1 galaxy would resemble that of Seyfert 2 galaxies, and, further, we would expect to see a noticeable contribution to the spectrum from gas hundreds of parsecs from the central source. It is possible that the high ionization region in Seyfert 2 galaxies is obscured by a torus, but this does not explain the absence of a low ionization component in NGC 5548. Not only do our models show that the narrow-line spectrum can be well fitted without such a component, but it is clear that the NLR of NGC 5548 is dominated by high ionization gas that must be located close to the central source.

A few Seyfert 1 galaxies do indeed show significant NLR emission at large distances from the central source. For example, *HST* observations of NGC 4151 (Evans et al. 1993; Hutchings et al. 1997) reveal an array of knots and filaments out to a kiloparsec that are almost certainly ionized by the central continuum. It may be that some Seyfert 1 galaxies, such as NGC 4151, have extended emission line regions and narrow lines in their spectra that closely resemble Seyfert 2 galaxies. Cohen (1983) studied the optical narrow line spectra of a group of Seyfert 1 galaxies and found some resemblance although, as a group, they appeared to be of somewhat higher ionization. Certainly, some of the galaxies in his study have spectra that are indistinguishable from those of type 2 Seyferts, but others, like NGC 5548, appear to be dominated by high ionization lines, a condition that appears to be rare among Seyfert 2 galaxies. It would be extremely interesting if one could determine if these high ionization objects are as compact as NGC 5548 appears to be. Unfortunately, optical spectra alone are insufficient for detailed modeling of the NLR, and thus far, accurate measurements of the narrow-line strengths in the UV have only been obtained for NGC 5548 and NGC 4151 (Ferland & Mushotzky 1982).

As we stated above, our finding that the inner component of gas is optically thin at the Lyman limit is based both on the absence of strong Mg II emission and the relative strength of the high ionization lines. If this is indeed true, not only for NGC 5548 but for other Seyfert 1 galaxies, it may be a clue to the origin of the inner narrow-line gas. Thin filaments or knots of reasonably high density ($\sim 10^7 \text{ cm}^{-3}$) could be the result of outflow from the BLR, either as condensations in an expanding intercloud medium or as “tails” of BLR clouds, driven out by radiation pressure. If so, the small physical depths of the clouds inferred from our modeling ($\sim 10^{14} \text{ cm}$) may constrain the sizes of their BLR progenitors. Note that there has been some recent success in models of the BLR using a component of optically thin clouds (Shields, Ferland, & Peterson 1995). There have been other studies suggesting that the clouds in the NLR are matter bounded or that some mix of radiation

bounded and matter bounded clouds exist (Wilson et al. 1997; Viegas-Aldrovandi 1988). Such a mix might give rise to the filamentary structure seen in some [O III] images of Seyfert galaxies rather than the typical molecular clouds found in spiral galaxies, and may give a clue about the origin of the NLR gas.

One other point regarding the NLR gas is that it appears that there may be some dust present within the outer components of the emitting region. Dust is certainly able to exist in clouds at this proximity to the central source, with dust temperatures reaching a few hundred K (Kraemer & Harrington 1986). Nevertheless, the history of the dust in this gas is unknown. Our finding that the outer clouds may not be purely radiation bounded would indicate that they are not simply interstellar molecular clouds that have an outer shell ionized by the central source. Our finding that there is probably dust mixed in with this gas will be important in determining the origin of this component.

Finally, Moore et al. (1996) find a correlation of ionization potential of the narrow emission lines with velocity width in NGC 5548. Combined with our finding that, to first order, the ionization level decreases with distance, this indicates that the radial velocities decrease with increasing distance. This trend is also seen in a more direct fashion in spatially resolved spectra of the inner NLR in NGC 4151 (Hutchings et al. 1997).

5. Conclusions

We have analyzed UV and optical spectra of the Seyfert 1 galaxy NGC 5548 that were obtained when it was at an historical minimum. We were able to isolate the narrow emission line components (which do not vary in flux on short time scales), due to the relative weakness of the more rapidly variable broad emission lines that are usually blended with the narrow components. We have constructed photoionization models of the narrow-line

region of this galaxy, and are able to successfully match the observed dereddened ratios of a large number of emission lines to within the errors, with the exceptions noted in Section 3.3. Since we used the best direct observational evidence of the shape of the ionizing continuum, rather than making adjustments based on fitting emission line ratios, the quality of this fit is particularly satisfying. The fact that a good fit was obtained for the permitted emission lines, such as C IV $\lambda 1549$, and the forbidden lines, such as [Ne III] $\lambda 3869$, [O III] $\lambda 5007$, [O II] $\lambda 3727$, [N II] $\lambda 6584$, etc., indicates that the range of physical conditions assumed in these models is approximately correct.

From our analysis and modeling of these spectra, we can make several statements regarding the physical conditions in the NLR of NGC 5548. First, it is clear that the principal source of ionization in the NLR of NGC 5548 is the central continuum source. This conclusion is borne out by the quality of the fit to the emission line spectrum. The NLR covering factor is reasonably small ($C = 0.11$), so the NLR gas does not need to intercept much of the ionizing continuum to produce the observed emission lines fluxes. A second conclusion is that the highly ionized gas in the inner part of the NLR appears to be optically thin at the Lyman limit ($\tau_0 \approx 2.5$), which yields constraints on the physical depths of these clouds and may provide a clue to their origin. We have also presented evidence for supersolar abundances in the inner portion of the NLR, and dust in the outer portion.

The most important conclusion that we have reached in this study is that the NLR of NGC 5548 is physically compact, with the majority of emission coming from a distance ≤ 70 pc from the nucleus. By contrast, the unified model of Seyfert galaxies suggests that the *physical* dimensions of the NLR in Seyfert 1 and 2 galaxies should be similar. Additional studies of the type that we have presented in this paper, particularly of other Seyfert 1 galaxies, are important for testing this aspect of the unified model.

We thank the referee, Andrew Wilson, for helpful comments and suggestions. We are

grateful to Fred Bruhweiler and Pat Harrington for helpful discussions on the physical properties of iron and the availability of atomic data. S.B.K. and D.M.C. acknowledge support from NASA grant NAG 5-4103. A.V.F acknowledges support from NASA grant NAG 5-3556, and B.M.P. acknowledges support from NSF grant AST-9420080.

REFERENCES

- Antonucci, R., ARA&A, 31, 473
- Clavel, J., et al. 1991, ApJ, 366, 64
- Cohen, R.D. 1983, ApJ, 273, 489
- Crenshaw, D.M., Boggess, A., & Wu, C.-C. 1993, ApJ, 416, L67 (Paper I)
- Crenshaw, D.M., & Peterson, B.M. 1986, PASP, 98, 185
- Draine, B.T., & Lee, H.M. 1984, ApJ, 285, 89
- De Robertis, M.M., & Osterbrock, D.E. 1984, ApJ, 286, 171
- Evans, I.N., Tsevtanov, A., Kriss, G.A., Ford, H.C., Caganoff, S., & Koratkar, A.P. 1993, ApJ, 417, 82
- Ferland, G.J. 1992, in The Nearest Active Galaxies, ed. J. Beckman, L. Colina, & H. Netzer (Madrid: CSIC Press), p. 75
- Ferland, G.J., & Mushotzky, R.F. 1982, ApJ, 262, 564
- Ferland, G.J., & Osterbrock, D.E. 1986, ApJ, 300, 658
- Ferland G.J., et al. 1996, ApJ, 416 683
- Filippenko, A.V. 1985, ApJ, 289, 475
- Filippenko, A.V., & Halpern, J.P. 1984, ApJ, 285, 458
- Heckman, T.M., et al. 1997, ApJ, 482, 114
- Hutchings, J.B. et al. 1997, ApJ, in press
- Kinney, A.L., et al. 1991, ApJ, 377, 100
- Koratkar, A.T., Evans, I., Pesto, S., & Taylor, C. 1997, ApJ, in press
- Korista, K.T., et al. 1995, ApJS, 97, 285

- Koski, A.T. 1978, ApJ, 223, 56
- Kraemer, S.B. 1985, Ph.D. thesis (University of Maryland)
- Kraemer, S.B., & Harrington, J.P. 1986, ApJ, 307, 478
- Kraemer, S.B., Wu, C.-C., Crenshaw, D.M., & Harrington, J.P. 1994, ApJ, 435, 171
- Krolik, J.H., Horne, K., Kallman, T.R., Malkan, M.A., Edelson, R.A., & Kriss, G.A. 1991, ApJ, 371, 541
- Lambert, D.C., & Luck, R.E. 1978, MNRAS, 183, 79
- MacAlpine, G.M. 1988, PASP, 100, 65
- Marshall, H.L., et al. 1997, ApJ, 479, 222
- Mathis, J.S., Ruml, W., & Norsieck, K.H. 1977, ApJ, 217, 425
- Miller, J.S., & Goodrich, R.W. 1990, ApJ, 355, 456
- Moore, D., Cohen, R.D., and Marcy, G.W. 1996, ApJ, 470, 280
- Murphy, E.M., Lockman, F.J., Laor, A., & Elvis, M. 1996, ApJS, 105, 369
- Oliva, E. 1997, in Emission Lines in Active Galaxies: New Methods and Techniques, ed. B.M. Peterson, F.-Z. Cheng, & A.S. Wilson (San Francisco: Astronomical Society of the Pacific), ASP Conference Series, 113, 288
- Osterbrock, D.E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, Univ. Science Books)
- Peterson, B.M. 1987, ApJ, 312, 79
- Peterson, B.M., et al. 1991, ApJ, 368, 119
- Peterson, B.M., et al. 1994, ApJ, 425, 622
- Peterson, B.M., Pogge, R.W., Wanders, I., & Smith, S.M. 1995, PASP, 107, 579
- Pogge, R.W. 1989, ApJS, 71, 433

- Pradhan, A.K., & Peng, J.F. 1995, in *The Analysis of Emission Lines*, ed. R. Williams & M. Livio (Cambridge: Cambridge Univ. Press), STScI Symposium Series, 8, p.8
- Rosenblatt, E.I., Malkan, M.A., Sargent, W.L.W., & Readhead, A.C.S. 1992, *ApJS*, 81, 59
- Savage, B.D., & Mathis, J.S. 1979, *ARA&A*, 17, 73
- Schmitt, H.R., & Kinney, A.L. 1996, *ApJ*, 463, 498
- Seab, C.G., & Shull, J.M. 1983, *ApJ*, 275, 652
- Seaton, M.J. 1978, *MNRAS*, 185, 5P
- Shields, J.C., Ferland, G.J., & Peterson, B.M. 1995, *ApJ*, 441, 507
- Shuder, J.M., & Osterbrock, D.E. 1981, *ApJ*, 250, 55
- Shull, J.M., & Van Steenberg, M.E. 1985, *ApJ*, 294, 599
- Storchi-Bergman, T., Wilson, A.S., Mulchaey, J.S., & Binette, L. 1996, *Å*, 312, 357
- Tran, H.D. 1995, *ApJ*, 440, 597
- Turner, T.J., & Pounds, K.A. 1989, *MNRAS*, 240, 833
- Viegas-Aldrovandi, S.M. 1988, *ApJ*, 330, L9
- Viegas-Aldrovandi, S.M., & Contini, M. 1989, *A&A*, 215, 253
- Wamsteker, W., et al. 1990, *ApJ*, 354, 446
- Wanders, I., & Peterson, B.M. 1996, *ApJ*, 466, 174
- Wilson, A.S. 1997, in *Emission Lines in Active Galaxies: New Methods and Techniques*, ed. B.M. Peterson, F.-Z. Cheng, & A.S. Wilson (San Francisco: Astronomical Society of the Pacific), ASP Conference Series, 113, 264
- Wilson, A.S., Binette, L., & Storchi-Bergmann, T. 1997, *ApJ*, 482, 131
- Wilson, A.S., & Ulvestad, J.S. 1982, *ApJ*, 260, 56

Wilson, A.S., Wu, X., Heckman, T.M., Baldwin, J.A., & Balick, B. 1989, ApJ, 339, 729

Zheng, W. et al. 1997, ApJ, 475, 469

Fig. 1.— Optical ground-based spectra of NGC 5548, obtained when the continuum and broad-line fluxes were at a very low level. The upper spectrum is offset by a constant flux of $5 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$.

Fig. 2.— UV to X-ray continuum of NGC 5548, in luminosity assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Observed UV and X-ray points and dotted line fit are from Krolik et al. (1991). Our broken power-law fit ($\alpha = -1.4, -0.4$) is given by the solid line. The *EUVE* continuum point described in the text is given for comparison.

Table 1. Narrow-line ratios for NGC 5548 (relative to $H\beta^a$)

	Reddening ^b		σ^c
	Observed	Corrected	
Ly α λ 1216	14.60	22.01	(± 7.53)
N V λ 1240	1.82	2.70	(± 0.95)
O I λ 1302	0.81	1.15	(± 0.60)
Si IV/O IV] λ 1400	2.10	2.88	(± 0.99)
N IV] λ 1486	0.30	0.40	(± 0.15)
C IV λ 1550	10.73	14.22	(± 4.10)
He II λ 1640	1.22	1.60	(± 0.50)
O III] λ 1663	0.63	0.82	(± 0.26)
Si III] λ 1892	0.24	0.32	(± 0.13)
C III] λ 1909	2.18	2.91	(± 0.83)
O III]/C II] λ 2323	0.37	0.51	(± 0.23)
[Ne IV] λ 2423	0.24	0.31	(± 0.15)
[O II] λ 2470	0.21	0.27	(± 0.11)
Mg II λ 2800	<0.15	<0.18	
O III λ 3133	0.45	0.50	(± 0.18)
He II λ 3204	0.15	0.17	(± 0.07)
[Ne V] λ 3346	0.57	0.62	(± 0.13)
[Ne V] λ 3426	1.70	1.84	(± 0.30)
[Fe VII] λ 3588	0.21	0.23	(± 0.07)
[O II] λ 3727	0.79	0.84	(± 0.14)
[Fe VII] λ 3760	0.45	0.48	(± 0.08)
[Ne III] λ 3869	1.25	1.32	(± 0.18)
H ζ + He I λ 3889	0.27	0.28	(± 0.18)
[Ne III] + He ϵ λ 3967	0.42	0.44	(± 0.07)

Table 1—Continued

	Reddening ^b		σ ^c
	Observed	Corrected	
[S II] $\lambda 4072$	0.12	0.13	(± 0.03)
H δ $\lambda 4102$	0.21	0.22	(± 0.05)
H γ $\lambda 4340$	0.45	0.46	(± 0.09)
[O III] $\lambda 4363$	0.75	0.77	(± 0.11)
He II $\lambda 4686$	0.22	0.23	(± 0.05)
H β $\lambda 4861$	1.00	1.00	
[O III] $\lambda 4959$	2.61	2.60	(± 0.36)
[O III] $\lambda 5007$	8.13	8.07	(± 0.88)
[Fe VII] $\lambda 5721$	0.21	0.20	(± 0.05)
He I $\lambda 5876$	0.22	0.21	(± 0.05)
[Fe VII] $\lambda 6087$	0.48	0.45	(± 0.08)
[O I] $\lambda 6300$	0.33	0.31	(± 0.07)
[O I] $\lambda 6364$	0.11	0.10	(± 0.03)
[Fe X] $\lambda 6374$	0.18	0.17	(± 0.06)
[N II] $\lambda 6548$	0.27	0.25	(± 0.06)
H α $\lambda 6563$	3.30	3.06	(± 0.44)
[N II] $\lambda 6583$	0.82	0.76	(± 0.15)
[S II] $\lambda 6716$	0.36	0.33	(± 0.07)
[S II] $\lambda 6730$	0.36	0.33	(± 0.07)
[O II] $\lambda 7325$	0.21	0.19	(± 0.06)
[S III] $\lambda 9069$	0.45	0.39	(± 0.09)
[S III] $\lambda 9532$	0.79	0.68	(± 0.13)

^aFlux (H β) = $6.7 (\pm 0.7) \times 10^{-14}$ ergs s⁻¹ cm⁻².

^bCalculated using $E_{B-V} = 0.07$ mag.

^cEstimated uncertainty in the reddening-corrected ratio.

Table 2. Line Ratios from model components

	INNER ^a	INNER ^a	OUTER ^b	OUTER ^b
	(solar)	(2x solar)	(no dust)	(dust)
C III λ 977	1.16	0.70	0.03	0.03
N III λ 990	0.16	0.11	0.00	0.00
O VI λ 1036	1.43	1.12	0.00	0.00
Si III λ 1206	0.05	0.05	0.02	0.02
O V λ 1216	1.94	1.64	0.00	0.00
Ly α λ 1216	36.24	35.59	38.02	20.26
N V λ 1240	2.02	1.86	0.00	0.00
C II λ 1334	0.05	0.12	0.13	0.06
Si IV λ 1398	0.52	0.54	0.08	0.06
O IV] λ 1402	2.67	2.52	0.04	0.05
S IV] λ 1417	0.14	0.13	0.01	0.01
N IV] λ 1486	1.91	1.69	0.03	0.03
C IV λ 1550	30.87	30.08	0.66	0.45
[Ne V] λ 1575	0.04	0.05	0.00	0.00
[Ne IV] λ 1602	0.31	0.31	0.01	0.02
He II λ 1640	2.64	2.39	1.57	1.71
O III] λ 1663	2.86	2.73	0.26	0.30
N III] λ 1750	0.92	0.99	0.16	0.19
[Ne III] λ 1815	0.03	0.03	0.00	0.00
Si III] λ 1883	0.00	0.00	0.05	0.05
Si III] λ 1892	0.31	0.42	0.20	0.20
C III] λ 1909	8.08	8.78	2.19	1.98
[O III] λ 2321	0.51	0.59	0.04	0.05
C II] λ 2326	0.07	0.10	1.37	1.09

Table 2—Continued

	INNER ^a (solar)	INNER ^a (2x solar)	OUTER ^b (no dust)	OUTER ^b (dust)
[Ne IV] λ 2423	0.03	0.03	0.26	0.29
[O II] λ 2470	0.01	0.02	0.29	0.31
[Mg V] λ 2784	0.14	0.19	0.02	0.01
Mg II λ 2800	0.11	0.18	2.12	0.81
[Mg V] λ 2929	0.04	0.05	0.00	0.00
[Ne V] λ 2974	0.02	0.02	0.00	0.00
He II λ 3204	0.15	0.14	0.10	0.11
[Ne III] λ 3342	0.02	0.02	0.00	0.00
[Ne V] λ 3346	0.29	0.41	0.04	0.04
[Ne V] λ 3426	0.79	1.11	0.10	0.10
[N I] λ 3467	0.00	0.00	0.01	0.01
[Fe VII] λ 3588	0.11	0.16	0.01	0.00
[S III] λ 3722	0.01	0.01	0.04	0.04
[O II] λ 3727	0.00	0.00	1.61	1.70
[Fe VII] λ 3760	0.15	0.22	0.01	0.01
[S III] λ 3796	0.00	0.00	0.00	0.00
[Ne III] λ 3869	1.11	1.67	1.28	1.42
[Ne III] λ 3967	0.35	0.51	0.39	0.44
[S II] λ 4072	0.00	0.00	0.16	0.17
H δ λ 4100	0.26	0.26	0.26	0.26
H γ λ 4340	0.47	0.47	0.47	0.47
[O III] λ 4363	2.24	2.57	0.18	0.20
He I λ 4471	0.03	0.03	0.04	0.04
Mg I] λ 4571	0.00	0.00	0.03	0.03
He II λ 4686	0.36	0.33	0.23	0.25

Table 2—Continued

	INNER ^a	INNER ^a	OUTER ^b	OUTER ^b
	(solar)	(2x solar)	(no dust)	(dust)
[Ne IV] λ 4720	0.07	0.08	0.00	0.00
H β	1.00	1.00	1.00	1.00
[O III] λ 5007	3.02	4.43	17.63	18.05
[N I] λ 5198	0.00	0.00	0.29	0.30
[N I] λ 5200	0.00	0.00	0.23	0.23
He II λ 5412	0.03	0.03	0.02	0.02
[O I] λ 5577	0.00	0.00	0.02	0.02
[Fe VII] λ 5721	0.15	0.23	0.02	0.02
[N II] λ 5755	0.00	0.00	0.05	0.05
He I λ 5876	0.08	0.09	0.11	0.11
[Fe VII] λ 6087	0.22	0.34	0.03	0.03
[O I] λ 6300	0.00	0.00	1.51	1.51
[S III] λ 6312	0.01	0.02	0.06	0.07
[O I] λ 6364	0.00	0.00	0.50	0.50
[Fe X] λ 6374	0.13	0.13	0.00	0.00
[N II] λ 6548	0.00	0.00	0.62	0.68
H α λ 6563	2.80	2.80	2.97	3.00
[N II] λ 6584	0.00	0.00	1.81	2.01
[S II] $\lambda\lambda$ 6716, 6731	0.00	0.00	1.19	1.18
[O II] λ 7325	0.01	0.02	0.38	0.43
[S III] λ 9069	0.00	0.01	1.21	1.33
[S III] λ 9532	0.01	0.02	2.95	3.24
[S II] λ 10,300	0.00	0.00	0.11	0.11
[N I] λ 10,395	0.00	0.00	0.04	0.05
[N I] λ 10,404	0.00	0.00	0.03	0.03

^aU = $10^{-1.5}$, $N_H = 1 \times 10^7 \text{ cm}^{-3}$, $\tau_0 = 2.5$.

^bU = $10^{-2.5}$, $N_H = 2 \times 10^4 \text{ cm}^{-3}$.

Table 3. Line ratios from standard model^a and observations

	Model	Dereddened
Ly α λ 1216	37.10	22.01 (± 7.53)
N V λ 1240	1.00	2.70 (± 0.95)
O I λ 1302	—	1.15 (± 0.60)
Si IV/O IV] λ 1400	1.65	2.88 (± 0.99)
N IV] λ 1486	0.97	0.40 (± 0.15)
C IV λ 1550	15.80	14.22 (± 4.10)
He II λ 1640	2.11	1.60 (± 0.50)
O III] λ 1663	1.56	0.82 (± 0.26)
Si III] λ 1892	0.26	0.32 (± 0.13)
C III] λ 1909	5.14	2.91 (± 0.83)
O III]/C II] λ 2323	1.00	0.51 (± 0.23)
[Ne IV] λ 2423	0.13	0.31 (± 0.15)
[O II] λ 2470	0.15	0.27 (± 0.11)
Mg II λ 2800	1.12	<0.18
O III λ 3133	—	0.50 (± 0.18)
He II λ 3204	0.12	0.17 (± 0.07)
[Ne V] λ 3346	0.16	0.62 (± 0.13)
[Ne V] λ 3426	0.44	1.84 (± 0.30)
[Fe VII] λ 3588	0.06	0.23 (± 0.07)
[O II] λ 3727	0.81	0.84 (± 0.14)
[Fe VII] λ 3760	0.08	0.48 (± 0.08)
[Ne III] λ 3869	1.20	1.32 (± 0.18)
H ζ + He I λ 3889	—	0.28 (± 0.18)
[Ne III] + He λ 3967	0.37	0.44 (± 0.07)

Table 3—Continued

	Model	Dereddened
[S II] $\lambda 4072$	0.08	0.13 (± 0.03)
H δ $\lambda 4102$	0.26	0.22 (± 0.05)
H γ $\lambda 4340$	0.47	0.46 (± 0.09)
[O III] $\lambda 4363$	1.21	0.77 (± 0.11)
He II $\lambda 4686$	0.29	0.23 (± 0.05)
H β $\lambda 4861$	1.00	1.00
[O III] $\lambda 4959$	3.44	2.60 (± 0.36)
[O III] $\lambda 5007$	10.32	8.07 (± 0.88)
[Fe VII] $\lambda 5721$	0.08	0.20 (± 0.05)
He I $\lambda 5876$	0.09	0.21 (± 0.05)
[Fe VII] $\lambda 6087$	0.13	0.45 (± 0.08)
[O I] $\lambda 6300$	0.76	0.31 (± 0.07)
[O I] $\lambda 6364$	0.25	0.10 (± 0.03)
[Fe X] $\lambda 6374$	0.07	0.17 (± 0.06)
[N II] $\lambda 6548$	0.31	0.25 (± 0.06)
H α $\lambda 6563$	2.89	3.06 (± 0.44)
[N II] $\lambda 6583$	0.91	0.76 (± 0.15)
[S II] $\lambda \lambda 6716, 6730$	0.59	0.66 (± 0.10)
[O II] $\lambda 7325$	0.20	0.19 (± 0.06)
[S III] $\lambda 9069$	0.61	0.39 (± 0.09)
[S III] $\lambda 9532$	1.47	0.68 (± 0.13)

^a50% H β contribution from INNER (solar abundances) and 50% from OUTER (no dust).



